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PREBIOTIC COORDINATION CHEMISTRY
THE POTENTIAL ROLE OF TRANSITION-METAL COMPLEXES
IN THE CHEMICAL EVOLUTION

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PREBIOTIC COORDINATION CHEMISTRY
THE POTENTIAL ROLE OF TRANSITION-METAL COMPLEXES
IN THE CHEMICAL EVOLUTION¹

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1. Introduction

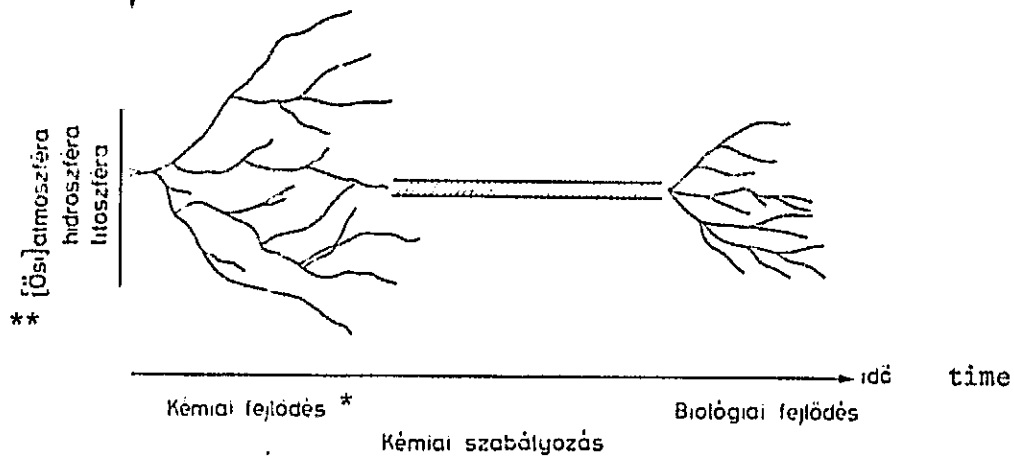
A fundamental change occurred about a quarter of a century ago in the research on the origin of life: simple speculations and philosophical considerations were replaced by experimental and theoretical examination of the problem. This change was made possible by advances in several branches of science and actually started with Oparin's book [1]. There is a simple answer to the fundamental question: how did life arise on Earth? - by chemical evolution and regulation. However formal this answer may be, it states unequivocally that no "vital force" played a role in the origin of life and that life evolved on Earth. */223

Figure 1 illustrates schematically the evolution of matter which led to the development of living systems. Making use of potential energy sources, some compound needed for the support of the functioning of the simplest living systems has been developed from the materials of the primeval atmosphere, hydrosphere and lithosphere. Research during the last two decades has considerably broadened our knowledge about the prebiotic formation of materials which are important for life; but it is only now that we begin to have an idea about the organizational processes which lead to a combination of compounds and reactions that made possible the development of self-reproducing homeostatic systems, separated from their environment by semipermeable membrane. The phenomena of chemical regulation obviously played a role during the phase of chemical evolution but they became decisive during the organizational

* Numbers in the margin indicate pagination in the foreign text.

¹ Based on a lecture presented at the April 6 session of Coordination Chemistry Working Committee.

Sketch of the origin of life (modified Calvin diagram)



*chemical development/chemical control/biological development

**ancient atmosphere/hydrosphere/biological development

Fig. 1.

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processes and although they were less obvious, they also play a determining role in the biological evolution.

We must find an answer to two questions concerning the role /224 of the transition-metal ions in the chemical evolution:

1. What could have been the role of the transition-metal complexes in the formation of the vitally important compounds before the appearance of life?

2. In what phase of chemical evolution did the transition-metal complexes become indispensable in the course of the formation of prebiotic systems and of their development toward the living stage?

There is justification, in view of the frequency of the transition-metal ions on Earth, to pose the first question. It is possible that the reactions of the various complexes have played an important role in the formation of materials needed for the chemism of primitive living systems. Justification for the second question is based on general experience, which reveals that transition-metal ions are found in all living systems from unicellular organisms to man - no life is possible without them. Therefore, it can be stated without exaggeration that the answer to the second question is decisively important for solving the problem of the origin of life.

In order to answer the first question, we must first of all clarify the nature and amount of transition-metal complexes in the "archetypal soup". Before the second question can be answered, the role of transition-metal complexes in the various organisms must first be analyzed.

2. The Potential Role of Transition-metal Complexes in the Primeval /225 Formation of the Vitally Important Compounds

2.1. Transition-metal Ions in the "Archetypal Soup"

The source of the transition-metal ion content of the primeval hydrosphere was obviously the primeval lithosphere. The composition

of Earth, the terrestrial crust and today's seawater is given in Table 1. Geological events probably have not caused major changes in the overall composition of the crust, although it is quite probable that certain transition metals were present 3 to 4 billion years ago in their elementary form. Moreover, it is probable that the various transition-metal carbides have been common components of the primeval lithosphere. However, we must assume that

TABLE 1: FREQUENCY OF THE TRANSITION METALS

Element	Earth % (%)	Frequency	
		Earth's Crust (ppm)	Seawater (mg/l)
Ti	0,05	4 400	0,001
V		135	0,002
Cr	0,26	100	0,00005
Mn	0,22	950	0,002
Fe	35	50 000	0,01
Co	0,13	25	0,0001
Ni	2,4	75	0,002
Cu		55	0,003
Zn		70	0,01
Mo		1,5	0,01

a) data source reference (3)

there have been considerable differences between the primeval and the current composition of seawater. At the start of the chemical evolution, the atmosphere completely differed as compared with today's atmosphere. No oxygen was present; H_2 , N_2 , CO_2 and CH_4 were the main components. The reducing character of the primeval atmosphere is supported by the fact that in the protominerals uranium and iron are present in their lower oxidation state, and all model calculations are in agreement with this. No oxygen could be found in the gaseous inclusions of protominerals. Under the influence of various energy sources (visible and UV radiation, electric arcing, heat, etc.), various reactive compounds are formed from the above-mentioned compounds of the primeval atmosphere. They served as the source of materials for the subsequent chemical evolution. From the viewpoint of complex-forming properties, the following compounds seem to be most important: HCN , $(CN)_2$, NH_3 and acetylene. Some of the other components of the

primeval atmosphere, hydrochloric acid and hydrogen sulfide reached the atmosphere as a result of gas release and vulcanic action. The most probable ligands of the primeval atmosphere are shown in Table 2.

TABLE 2: PREBIOTIC LIGANDS

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Prebiotic ligands:	H_2O , NH_3 , CO , CN^- , $(CN)_2$, CH_4 , S^2- , H^- , N_2 , CO_2
Secondary ligands:	amino acids, carbonic acids, peptides, heterocyclic and macrocyclic compounds, etc.

Differentiation between the primary and secondary ligands is rather arbitrary; the primary designation is meant simply to indicate that the ligand in question has been present during the initial phase of the chemical evolution while we consider as secondary ligands those molecules which have been formed in the course of chemical evolution and contain functional groups suitable to form complexes.

The exceptionally low iron content of today's seawater may be attributed to the low solubility of Fe(III) hydroxide and to the absence of complex-forming ligands. However, four billion years ago the oxidation state of iron was certainly lower and numerous complex-forming ligands have been available. From the viewpoint of dissolving action, the cyanide appears to be the most important of the primary prebiotic ligands, because it could have been formed easily under prebiotic conditions, it is easily soluble in water and the cyano complexes of the transition-metal ions are exceptionally stable. Therefore, we may obtain information about the transition-metal content of the "archetypal soup" from experiments, in which primeval minerals are subjected to extraction with dilute cyanide solutions [4]. The results of some such experiments are presented in Table 3.

The data referring to amphibolite and migmatite indicate that iron and copper could have been present in a slight but still sig-

TABLE 3: EXTRACTION OF TRANSITION METALS FROM MINERALS
WITH DILUTE CYANIDE SOLUTION^a

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Rock (ore)	Fe	CO	Cu	Mn	Mo
		mol x 10 ⁻³ x 10 ⁴			
Amphibolite	90	0	21	0,5	5
Migmatite	57	0	12	0	5
Wehrlite	360	8	9	0	5,2
Molybdenite ^b	27	2	5	0	120

^a 1 g of the comminuted rock was shaken with 0.014 M potassium cyanide solution. The equilibrium has been established in 36 hours.

^b The ore was together with the parent rock.

nificant concentration in the primeval ocean, even if the hydrosphere did not come in contact with ores rich in transition metals. Comparison of the data of Tables 1 and 3 indicates that it is probable that the transition-metal content of the primeval and today's seawater differed from each other by several orders of magnitude. The experiments carried out with wehrlite and molybdenite are of special interest because they indicate that at certain locations the concentration of the transition-metal complexes could have been quite high.

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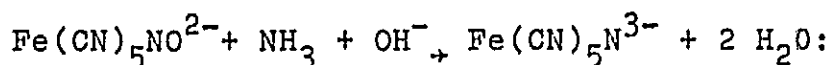
The possibility of the formation of cyano complexes has been mentioned also by Orgel [5] and according to Urey, cyano complexes might have played a role in the formation of gold seams [6].

In view of the probable presence of additional potential ligands in the "archetypal soup", it is probable that mixed ligand complexes of the transition-metal ions have been present. From this point of view, the following two atomic, isoelectric ligands: CN^- , CO , C^{2-} , N_2 , NO^+ are especially important. In spite of the identical electron structure of these ligands, there are substantial differences in their reactivity and complex-forming properties. These differences are due in part to differences in their electric charges and in part to different donor properties of the constituent atoms and the π electron system. Furthermore, it is important that the

electron acceptor properties of the empty π reducing paths differ also. It is worth mentioning that iron, which is obviously the first one of the transition-metal ions to be considered to play a decisive role in the chemical evolution, forms mixed-ligand complexes in all combinations of the isoelectric ligands:

The $\text{Fe}(\text{CN})_5\text{CO}^{3-}$ is formed from aquapentacyano ferrate (II) and carbon monoxide [7];

The $\text{Fe}(\text{N})_5\text{N}_2^{3-}$ is formed by the following reactions [8-10];



The formation of $\text{Fe}(\text{CN})_5\text{C}_2^{5-}$ or of its protonated form, is indicated by the spectral shift which appears when we bubble acetylene through a solution of aquapentacyanoferrate complex [11]. We should consider the coordination of these ligands when the state of oxidation of the central ion is low and the ligand makes counter-coordination possible. Under the reducing prebiotic conditions, the metal ions occur mostly in their lower valence state and some of the ligands of Table 2 have definite π acceptor properties. We must admit that those exotic transition-metal complexes that we can prepare today only by special laboratory techniques probably have been common molecular species on Earth four billion years ago.

Finally, a remark is in order concerning the occurrence of sulfido complexes. The sulfides of the transition metals are quite stable and their solubility is very low. Therefore, the sulfido complexes could have been present in the "archetypal soup" only in the form of mixed-ligand complexes. The cyanide ion is the only one to form stable complexes with the transition-metal ions which are not transformed with sulfide ions completely into the corresponding sulfide but form sulfido-cyano mixed-ligand complexes. The formation of the sulfido-cyano mixed-ligand complex is indicated by the rapid color change which accompanies the addition of the sulfide to the aquapentacyano ferrate (II) solution [11]. No reaction takes place when we add the sulfide to the hexacyanoferrate (II), or rather, a reaction is observed only after extended

heating or irradiation. If the sulfide ores are brought in contact with the cyanide solution, as in the above-mentioned molybdenite experiment, the transition-metal ions enter the solution obviously as sulfido-cyano mixed-ligand complexes.

2.2. The Effect of the Complex Formation on the Reactivity of the Ligands

The coordination of a ligand to a metal ion may increase or decrease the reactivity of that ligand [12]. Both effects could have a prebiotic importance. Increase of reactivity may enhance the formation of a vitally important compound or of its precursor. Decrease of the reactivity would stabilize these compounds, thereby assisting the enrichment of important substances. In connection with the effect on the reactivity of the ligands, several factors must be taken into account. The most important ones are listed below:

1. electrostatic effect;
2. electronic effect;
3. steric effect.

These effects are correlated with each other and the reactivity occurs as their result.

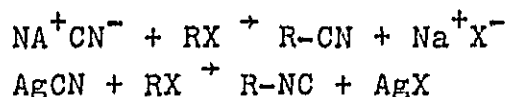
The coordination may change the electric charge of the reactants, which naturally could affect considerably the sign and the magnitude of the electrostatic interaction prevailing between them. This effect manifests itself in the entropy of activation.

Naturally, the coordination causes changes in the electron distribution of the ligand, which is reflected in the behavior of the atoms of the ligand with respect to nucleophilic or electrophilic reactants. This effect manifests itself primarily in the enthalpy of activation.

The defined spatial structure of the coordination sphere may lead to specific interactions between the coordinated ligands,

and may render certain reaction paths possible between the ligands and external reactants. This effect could affect considerably both the enthalpy of activation and the entropy. The steric factor may play an especially important role in the formation of macrocyclic compounds generated around the central metal ion.

In some cases, extraordinary effects of the coordination on the reactivity may be observed. For example, the reaction of alkali cyanides with alkyl halides yields alkyl nitriles; on the other hand, if we use silver cyanide or other complex cyanides instead of the alkali salt, the corresponding isonitriles are formed. /229 This differential behavior is obviously due to the fact that in the complex the cyanide is bound to the metal ion through the carbon atom:



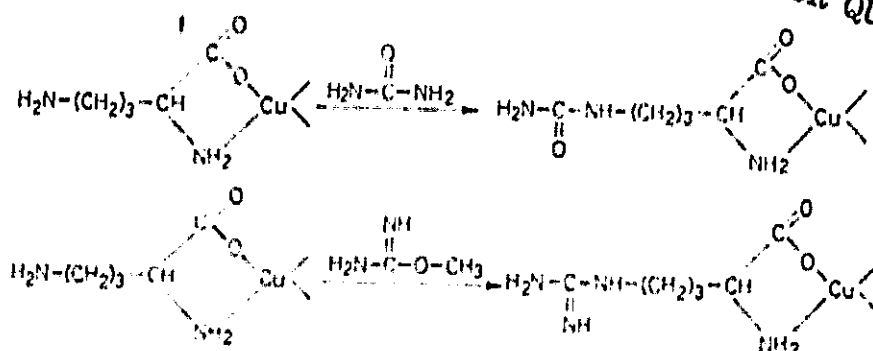
However, certain experimental results indicate that a small fraction of the coordinated cyanides is bound through the nitrogen atom [13-14]. (In multinuclear cyano complexes both the carbon and the nitrogen atom institute the bond). The cyanide is an effective catalyst of the benzoin condensation [15]. Transition and second-type metal ions inhibit the catalytic effect of the cyanide but by using sensitive methods to demonstrate the presence of benzoin, it is possible to prove a certain effect, even in the case of cyano complexes [16]. (The results of calculations exclude the possibility that the then observed catalytic effect is due to the cyanide dissociated from the complex). The first step of the catalytic reaction consists in the formation of cyan hydrine which may take place with the free cyanide or with cyanide bound at the nitrogen end.

One of the most important results of the prebiotic syntheses is the formation of adenine from hydrogen cyanide. Considering that the adenine is the formal pentamer of hydrogen cyanide, this is not really surprising. Coordination of the cyano groups may

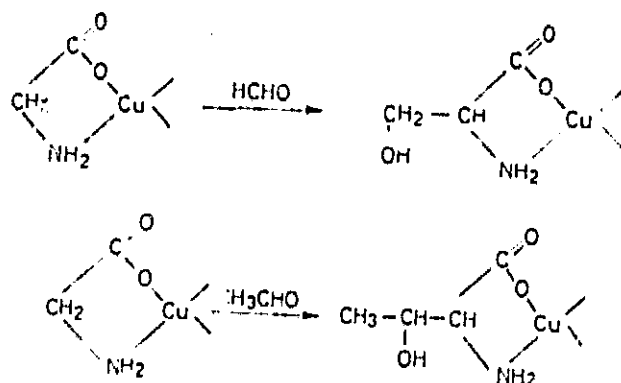
be advantageous also from the viewpoint of the heterocyclic compounds. The effect of coordination may either increase or decrease the reactivity of the cyanide ion. In other words, the enthalpy of activation may be either higher or lower than in the case of the reaction of the free cyanide. Even if the reactivity is decreased, it might be possible to enhance the reaction by complex formation in view of the increase of the entropy of activation. Depending on the composition and the structure of the cyano complex, the heterocyclic framework may be formed completely or partially within the coordination sphere by internal rearrangement. Unfortunately, we do not possess sufficient knowledge on the reactions of the cyano complexes to evaluate the effect of coordination in case of such processes. It seems probable that the more cyano groups are present in the coordination sphere, the more increased the entropy of activation. The fact that a fraction of the cyano groups is bound through the nitrogen and may facilitate the heterocyclic evolution. The hexacyano ferrate (II) and octocyano molybdate (IV) appear to be the most important complexes from the viewpoint of the prebiotic synthesis of heterocyclic compounds.

Decrease of the rate of the hydrolysis of the cyanide ion due to coordination may result in the accumulation of the cyanide ion. In the absence of metal ions, the hydrogen cyanide concentration during various prebiotic syntheses exhibits maximum as a function of time. It appears important to study the effect of metal ions on the various prebiotic synthesis pathways in general, and the role of the cyanide ion in particular.

The effect of coordination manifests itself differently in /230 the reactions of amino acids. The adjacent carboxyl and amino groups play a role in the complex formation. If the ligand is an α ω amino acid, the complex formation renders possible the selective reaction of the ω amino group. This principle was used for the preparation of ornithine [17] and arginine [18] from citrulline:



In the case of glycine, the formation of the Cu(II) complex inhibits the reactions of both functional groups. However, the CH_2 group is activated and, with aldehydes, the well-known Knoevenagel reaction takes place. In the reaction with formaldehyde serine [19], and with acetaldehyde treonine [20] is formed:



It is not quite clear whether this type of reaction has any prebiotic meaning; still, these experiences indicate that the complex formation may have influenced in various ways, the reactions of prebiotically important molecules.

2.3. Catalytic Effects

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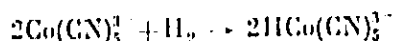
Under prebiotic conditions we may have to consider homogeneous or heterogeneous catalysis. The catalytic effects of var-

ious metals, in particular of iron and nickel appear to be quite probable. Reactions of such nature, as for example, the Fischer-Tropsch syntheses, possibly play a role in the formation of hydrocarbons, carbonic acids and even - as we will discuss in Chapter 2.4 - of heterocyclic compounds [21]. The catalytic effect of platinum metals is even more marked; however, in view of their rarity, it appears improbable that these effects should be taken into consideration under prebiotic conditions.

It is possible that metal ions and various metal complexes have been adsorbed on various primeval rocks. We have no experience concerning their catalytic effect.

The third group of catalysts consists of semiconducting metal oxides. We are aware of one case concerning their catalytic effect, with obvious prebiotic importance. It has been observed recently that in the presence of zinc oxide catalyst, upon exposure to UV radiation, the adenosine diphosphate is phosphorylated [22].

Phenomena of homogeneous catalysis may occur in the atmosphere and in the hydrosphere. The various volatile metal carbonyls may have played a role in gas-phase prebiotic reactions. In the liquid phase, the cyano complexes appear to be the most important compounds from the viewpoint of catalytic action. Among the cyano complexes, the pentacyano cobaltate (II) has been studied to the greatest extent as the catalyst of various processes [23]. The pentacyano cobaltate (II) reacts easily with molecular hydrogen, forming a hydrido complex



which reacts readily with various unsaturated compounds. In the involvement of the catalytic effect, the empty coordination place of the cobalt (II) complex plays an important role. Our knowledge about the catalytic effect of the coordinatively saturated cyano complexes is limited. The binuclear $\text{Ni}_2(\text{CN})_6^{4-}$ complex reduces butadiene to butene [24], which means that this complex catalyzes

the reduction of butadiene with borohydride or another reducing agent which is capable of reducing the $\text{Ni}(\text{CN})_6^{2-}$. Recently, we observed that the hexacyano ferrate (II) catalyzes the reduction of p-nitroaniline with borohydride [11]. There is hardly any doubt that in this reaction an iron complex with a coordination number lower than two plays a role. Of course, the borohydride reactions do not have any prebiotic importance. However, from the prebiotic point of view, it seems to be promising and necessary to study the catalytic effect of the various low-oxidation-level iron and nickel complexes.

2.4. Survey of the Experimental Results

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2.4.1. Formation of the Amino Acids

Bahadur [25] observed the formation of various amino acids as a result of the irradiation of an aqueous solution containing paraformaldehyde, iron (III), chloride and potassium nitrate with sunlight. He found, surprisingly, that the potassium nitrate concentration affects not only the amount but also the kind of amino acids which are formed (Table 4).

TABLE 4: INFLUENCE OF THE POTASSIUM NITRATE CONCENTRATION OF THE REACTION MIXTURE ON THE FORMATION OF AMINO ACIDS, ACCORDING TO BAHADUR

<u>% of KNO_3</u>	<u>Amino Acids Formed</u>
1	asparagine, serine, proline
0.5	asparagine, serine, proline, arginine, ornithine
0.25	asparagine, serine, proline, arginine, glycine, valine, histidine, asparaginic acid

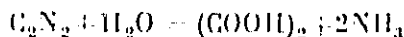
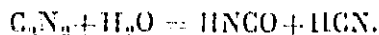
Only traces of a few amino acids could be found in the absence of iron (III) chloride. Lately, a number of metal ions were found to be effective from the viewpoint of the photosynthesis of amino acids [26]. According to Bahadur, Ranganayaki and Santamaria [27], the synthesis of the amino acids takes place even if the nitrogen

content of the atmosphere is the only source of nitrogen, and the aqueous paraformaldehyde solution is irradiated in the presence of colloidal molybdenum oxide. Should subsequent experimental studies confirm these results, they could be extremely important.

Oro, Kimbal, Fritz and Master [29] observed the formation of various amino acids upon heating an aqueous solution of formaldehyde and hydroxylamine. In an acid medium the yield reached 14%. The influence of various metal salts was also studied. With the exception of the molybdate and the vanadate, the various salts did not prove to be effective, and the iron chloride actually decreased - albeit slightly - the yield. However, the amount of the formed amino acids increased exponentially with the increase of the molybdenum concentration.

Ventilla and Egami have repeated these experiments [29]. They used a formaldehyde concentration of 0.25M, a hydroxylamine concentration of 0.05M and each of the following ions: Cu(II), Mn(II), Mo(VI), Fe(III) and Zn(II), had a concentration of 10^{-4} M. They found that peptides were also formed in addition to the formation of amino acids, but in the absence of suitable control tests, it is not possible to evaluate the effect of the metal ions.

Recently we proved the formation of glycine during the acid hydrolysis of the $\text{H}_2\text{Cu}_2(\text{CN})_4\text{C}_2\text{N}_2$ complex [30]. This complex may be prepared by adding dropwise to the strongly chilled and stirred, 233 concentrated potassium cyanide solution, a concentrated copper (II) sulfate solution until the copper:cyanide ratio reaches the 1:3 level. The black precipitate is filtered off, washed with water, ethanol and finally with ether and dried over P_2O_5 . Upon boiling with hydrochloric acid, 1 mole of coordinated cyanogen yields 0.13 mole of glycine. The hydrolysis of free cyanogen may be described by the following equations:



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These results indicate that a portion of the coordinated cyanogen hydrolyzes according to the following stoichiometric relation:



In case of alkaline hydrolysis, the formation of alanine may be observed.

Glycine is also the main product of the photolysis of the dilute (10^{-2}M) solution of hexacyano ferrate (II) and octacyano molybdate (IV) in the presence of formaldehyde but many other amino acids are formed in lesser amounts [31]. The yield of all amino acids calculated on the basis of the complex, expressed as glycine, reaches 25%. This is higher than the yield of any of the prebiotic amino acids published up to now, and indicates that the study of this aspect of the reactions of metal complexes may be fruitful. The reactions of mixed-ligand complexes containing both the cyanide ion and cyanogen appear to be especially promising.

2.4.2. Formation of Peptides

The formation of peptides from amino acids in aqueous solution is not favored thermodynamically. The thermodynamic barrier may be removed in three ways:

1. By removing the water formed during condensation; i.e., by operating under water-free or nearly water-free conditions;
2. by using suitable connected reactions which supply the required free energy;
3. by using an external energy source.

The esters of amino acids in organic solvents (such as ethanol, methanol or chloroform) yield oligopeptides in the presence of various metal salts [32]. Brach, Louembe and Spach [33] also observed the formation of octapeptides in the solution of glycine methyl ester in ethanol in the presence of Cu Cl_2 . In aqueous solution they noted no reaction. For this reason, this otherwise interesting

result does not seem to be important from the prebiotic viewpoint.

Calvin [2] has discovered that HCN, cyanimide and several /234
other similar compounds promote the formation of oligopeptides from amino acids in a dilute aqueous solution. In these systems the indirect hydrolysis of the energy-rich compounds supplies the free energy needed to form the peptide bond. Inasmuch as these reactions require the presence of free or protonated carboxyl and amino groups, and as they take place in fairly strongly acid medium, it appears improbable that the transition-metal ions would promote the formation of peptides in these systems.

Bahadur used the third possibility [26]. He found that many peptides are formed from amino acids in the presence of sugars and various transition-metal ions in the course of photochemical reactions. However, the yield is so low (he does not give numerical values, indicating simply the intensity of the spots of amino acids identified by means of paper chromatography), that even if these results were to be confirmed, they would not supply a valuable support for the prebiotic synthesis of peptides.

2.4.3. Formation of Nucleic Bases

Hayatsu [34] was the first to observe the formation of nucleic bases in a Fischer - Tropsch type synthesis, using a mixture of CO, H₂ and NH₃. Yand and Oro [21] studied these processes in great detail, using paper chromatography UV and IR spectra, for the identification of the products. By using industrial Fe - Ni alloy catalyst and a gas mixture with the composition of CO:H₂:NH₃ = 1:2:0.44 at 650°C, under a pressure of three atmospheres, they noted the formation of the following compounds (the yield refers to NH₃):

<u>Compound</u>	<u>Yield %</u>
carbamide	0.475
biuret	0.178
melamine	1.220
guanyl carbamide	0.353
adenine	0.507
guanine	0.158
cytosine	0.127
cyanuric acid	0.810

In the photolysis of octacyano molybdate (IV) in the presence of formaldehyde, adenine and several not yet identified imidazole-type compounds are formed [31]. In 0.01 to 0.1 molar solutions with respect to the complex, the reaction takes place within a few hours and the yield of the adenine, as calculated for the complex, amounts to 5 to 10%. It was not found possible to find other nucleic bases by chromatographic methods. In the photolysis of the hexacyano ferrate (II) complex under identical conditions no adenine is formed.

2.4.4. Formation of Porphyrins

The importance of metal ions in the biochemical reactions of /235 tetrapyrrole pigments is obvious. Furthermore, the experiments indicate unequivocally that complex formation plays an important role in the formation of these macrocyclic compounds from pyrrole and formaldehyde. Hodgson and Baker [35] studied the effect of various metal ions and comminuted ores on the formation of porphyrin from pyrrole and formaldehyde. In their experiments they used a metal-ion concentration of 0.05 and a paraformaldehyde concentration of 0.03 M. The solutions were refluxed for 42 to 125 hours. From the metal ions, Ni (II), with a yield of 8 micrograms, was found to be the most efficient. Addition of sandstone, slate or carbonates to the reaction mixture raised the yield to 100 micrograms. Unfortunately, the short publication does not contain much fundamental information, rendering evaluation of the results difficult. For this reason we have repeated the experiments [30]. In our experiments the concentration ratios agreed with the given data. In every case, the volume of the reaction mixture was 100 ml. In addition to the effect of the various metal sulfates, we also studied the effect of $\text{Ni}(\text{CN})_4^{2-}$ and $\text{Fe}(\text{CN})_6^{4-}$. The results are summarized in Table 5.

In agreement with the experience of Hodgson and Baker, the data indicate that the nickel ion promotes the formation of porphyrin but in contradiction with their findings, we found that sandstone reduces the yield. In view of the fact that during the early stages

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TABLE 5: EFFECT OF CERTAIN METAL IONS ON THE YIELD
OF PREBIOTIC PORPHYRIN SYNTHESIS

Added salt	Yield	
	μg	$\mu\text{g} \cdot 10^4$
FeSO_4	0.1 - 0.5	2.5 - 4
NiSO_4	0.1 - 1.6	9 - 35
CuSO_4	6 - 8	130 - 175
NiSO_4 sandstone	1.2 - 1.6	26 - 35
$\text{K}_3\text{Fe}(\text{CN})_6$	0.2 - 0.6	4 - 13
$\text{K}_3\text{Fe}(\text{CN})_6$	0.6 - 1.0	13 - 22
$\text{K}_3\text{Fe}(\text{CN})_6$	20 - 60	40 - 1300

a) reaction time 64 hours

b) 0.3 grams sandstone in
100 m/l reaction mixture

of chemical evolution the transition-metal ions were present probably in the form of cyano complexes, it is noteworthy that the hexacyano ferrate (II) increases the yield considerably.

3. The Potential Role of Transition-metal Complexes in the Organizational Phase of Chemical Evolution /236

3.1. Occurrence and Biochemical Functions of Transition-metal Ions in Present-day Living Organisms

Although it is not unequivocally accepted that the chemism of the simplest living organisms - in the current meaning of the term - and of the precursor "probiotics" were substantially identical, an examination of the role of transition-metal ions in present-day organisms is a logical starting point for discovering the role played by the metal ions during the transitional period of chemical evolution.

The concentration of transition-metal ions in living organisms varies extraordinarily; this may be attributed in part to properties of the various species and in part to individual peculiarities of the different monocellular organisms, plants and animals, and to the distribution frequency of the various microelements in their environment. For this reason, the data presented in Table 6 should be considered only as averages. The current composition of the organisms is obviously the result of long-range chemical and

TABLE 6: Transition metal ion concentration in different compounds^{a, b}

6. táblázat

Az átmenetifém-ionok koncentrációja különböző szervezetekben^a

Elem	Szervezet						
	Plankton	Barna alga	Baktériumok	Gombák	Rovarok	Halak	Emlések
Ti	80	12	--	--	160	0,2	<0,7
V	5	2	--	0,07	0,15	0,11	<0,1
Cr	3,5	1,3	--	1,5	--	0,2	0,3
Mn	75	53	30	25	10	0,8	0,2
Fe	3500	690	250	130	200	30	160
Co	5	0,7	--	0,5	0,7	0,5	0,3
Ni	30	3	--	1,5	9	1	<1
Cu	200	11	42	15	50	8	2,1
Zn	2600	150	--	150	400	80	160
Mo	1	0,45	--	1,5	0,6	1	1

^a Az adatok forrása [37].^b A koncentráció ppm-ben van megadva és a szervezetanyag-tartalmára vonatkozik.^a data source (37)

^b concentration given in parts/mil. and ref. to extract content biochemical evolution. This sounds like a cliché but it diminishes the value of statements, such as "The chemical composition of living organisms reflects to a certain extent the composition of the environment in which they evolved" [38]; or (in view of the fact that life evolved first in the sea or salt-water lakes) "The composition of the oceans left an ineradicable trace in the chemistry of all cells and organisms" [39]. Analysis of the data indicates that the enrichment factor (which is the quotient of the concentration in the terrestrial crust and in the organism of the given element) is quite uniform for different organisms; however, frequent and occasionally extreme deviations from the general behavior are encountered [40-43]. According to Banin and Navrot [40], the logarithm of the enrichment factor as a function of the ion potential (IP = the quotient of the positive charge of the ion and its radius) yields a curve, which at IP = 5 exhibits a minimum, regardless of the type of the living organism. Moreover, seawater exhibits a substantially identical behavior. However, it must be taken into consideration that three billion years ago the transition-metal ion had a lower oxidation state, and accordingly a lower ion potential. Without doubt, the considerations of Banin and Navrot rest on logical foundations and

by themselves they invalidate one of the assumptions of the so-called controlled panspermia theory [38]. According to that theory "the occurrence of elements which are extremely rare in living organisms on the Earth may indicate the extraterrestrial origin of life". Crick and Orgel stated incorrectly that the occurrence of molybdenum in living organisms with respect to other elements is abnormal.

The similarity in the distribution of transition-metal ions without regard to the type of the living organism may be due to the fact that compounds with very similar complex-forming properties participate in the metabolism of the various organisms. Strong deviation from the general behavior may be attributed either to the presence of agents with specific complex-forming properties or to the great enrichment of a specific metal ion in the environment or to both of these factors. In the so-called accumulating organisms these deviations may indeed be extraordinary. For example, while the nickel content of plants ranges from 1 to 30 ppm, with respect to dry matter, in *Hybanthus floribundas*, an amount not less than 8000 ppm was found [44]. It follows from the complex-forming properties of most biochemically important compounds that the presence of transition-metal ions in the organism does not necessarily mean that they play a vital role in the chemism of a given organism. Even in the case of accumulating plants and animals, it is not certain that the enriched ions are essential from the viewpoint of vital processes. Rather, it may be that these organisms developed a specific biochemical system which eliminates the toxic effect of large concentrations of the transition metal ions.

In the living organisms, the transition-metal ions act as components of enzymes and of electron and oxygen carriers. There is no sharp boundary between the enzymes and the carriers; the latter usually represent a portion of the enzyme systems. The metal ions must be incorporated into certain organic molecules to enable them to exert their function. In the course of the chemical evolution some specific molecules were developed, enabling the transportation of metal ions to the place of enzyme synthesis. This is especially important in the case of Fe(III) because of its great

tendency toward hydrolysis. However, it is obvious that in this case this transport mechanism has evolved during a later period of the evolution when the redox potential reached the required value. It is well known that a large part of the enzymes contain loosely or strongly bound metal ions. Without doubt, iron is the most important transition-metal ion from this viewpoint and it appears justified to state that "any form of life is extremely improbable in the absence of iron" [45]. Copper, zinc, manganese and molybdenum also appear to be indispensable for most of the enzymes. The distinctive role of iron in each phase of chemical and biochemical evolution is due to the extraordinarily varied chemical actions and wide distribution of the iron compounds. /238

3.2. Evolution of the Enzymes

According to Calvin, the enzymes evolved in the course of autocatalytic processes [2]. For example, when it became necessary to decompose hydrogen peroxide, the $\text{Fe}^{3+}/\text{Fe}^{2+}$ redox system may have served as catalyst. However, this system has a low efficiency. On the other hand, the iron ions promote the formation of the tetrapyrrole ring. Formation of porphyrin from pyrrole and formaldehyde requires a six-equivalent oxidation. This oxidation is promoted by hydrogen peroxide and by iron ions. The formed iron-porphyrin complex is a much more effective catalyst of the decomposition of hydrogen peroxide than the iron aqua-ions. The catalytic action increased even more when the complex is incorporated into a suitable albumin molecule. This is an excellent example, but this principle cannot be considered as being generally valid for the development of enzymes. The iron complexes in the form of both heme and non-heme albumins are the most often encountered biocatalysts. It is a logical, albeit moot, assumption that the biocatalysts of today's anaerobic bacteria are closely related to those of the probionts. It may be suspected in particular of certain types of ferredoxines that either they or their precursors have been the first redox catalysts of living organisms [46]. The redox potential of the various ferredoxine-type systems varies from -450 to +350 mV, thereby making possible

the catalysis of various redox reactions. This agrees with the assumption of Baltischeffsky [47], according to which the biological electron transport started from a value close to the potential of the hydrogen electrode and when molecular oxygen became available, it reached the value of the oxygen electrode. However, it is doubtful that the ferredoxine precursor was identical with or even closely related to the previously proposed ferredoxine model compounds. The appearance of the enzymes presupposes an albumin synthesis involving a well developed control system interacting with DNA (RNA). For this reason, we believe that the prototypes of enzymes may be found among the high-molecular-weight compounds containing transition-metal ions, which may be formed also under prebiotic conditions. The polymerization of hydrogen cyanide may be considered as the most probable process, leading to the prebiotic formation of the polymer. We found [48] that in the presence of the cyano complexes of transition metals, the polymer absorbs selectively the various transition-metal ions and the formed substances are the catalysts of various redox processes, such as the auto-oxidation of ascorbic acid. The effect of pentacyano cobaltate (II) on the polymerization is especially interesting. Even when the amount of the cobalt (II) present is low (less than 0.2% of the cyanide concentration), the reaction is greatly hindered in view of the fact that the hexacyano cobaltate (III) has /239 absolutely no effect on the polymerization process, the effect of the cobalt (II) complex is probably due to the nature of free radicals.

4. Conclusions

In approaching the extremely involved and complex problem of the origin of life, consideration of the coordination chemistry appeared not only as a possibility but as a necessity. The first model experiments appear to be promising because it was found possible to increase considerably the efficiency of prebiotic-type syntheses by means of transition-metal complexes. It is especially significant that in some instances various types of vitally important substances (nucleic bases, amino acids) are formed simultaneously. There is ground to hope that systematic studies in this field will clarify

the role of transition-metal complexes in the organizatorial phase of chemical evolution. It is obvious that researchers working in the fields of the chemistry of cyano and carbonyl complexes, and of the catalytic effect of transition-metal complexes are best suited to study these aspects of the attractive and interesting problem of the origin of life.

REFERENCES

1. Oparin, A.I., Proiskhozdenie Zhizny [The Origin of Life], Izd. Moskovski Rabochii, Moscow, 1924.
2. Calvin, M., Chemical Evolution, Oxford University Press, New York/Oxford, 1969.
3. Mason, B., Principles of Geochemistry, 3rd. ed., J. Wiley and Sons, New York, 1966.
4. Beck, M.T., Ling, J., Naturwiss., 64, 91 (1977).
5. Orgel, L.E. in, The Origin of Life and Evolutionary Biochemistry, Edited by, D.K. Soese, S.W. Fox, G.A. Deborin, T.W. Pavlovskaya, Plenum Publishing Co., New York, 1974, 369, old.
6. Landis, V.J., J. Chem. Educ., 51, 565 (1974).
7. Hieber, W., Nast, R., Bartenstein, C., Z. anorg. allg. Chem., 272, 32 (1953).
8. Dozsa, L., Beck, T., In Proceedings of XIIIth Int. Conf. Coord. Chem., Cracow/Zakopane, 1970, Vol. 1, 27. old. /240
9. Dozsa, L., Szilassy, I. Beck, M., Magy. Kem. Folyoirat, 79, 45 (1973).
10. Yatsimirskii, K.B.; V.V. Nemoshkalenko, Yu. P. Nazarenko, V.G. Akeshin, V.V. Zhilinskaya, Yu. D. Tal'denko, Dokl. Akad. Nauk. 277, 1374 (1974).
11. Beck, M., Csabina S., Unpublished reports.
12. Jones, M.M., Ligand Reactivity and Catalysis, Academic Press, New York, 1968.
13. Gans, P., Gill, J.B., Griffin, M., J.S.C. Chem. Comm., 169 (1976).
14. Birk, J.P., Espenson, J.H., J. Amer. Chem. Soc., 90, 2266 (1968).
15. Stern, E., Z. phys. Chem., 50, 513 (1905).
16. Feigl, F., A. Caldas, Microchim. Acta, 992 (1955).
17. Kurtz, A.C., J. Biol. Chem. 122, 477 (1938).
18. Turba, F., Schuster, K.H., Z. Physiol. Chem., 283, 27 (1948).
19. Okawa, K., Sato, M., Chem. Abstr., 54, 328g (1950).

20. Sato, M., Okawa, K., Akabori, S., Bull. Chem. Soc. Japan, 30, 937 (1957).
21. Yank, C.C., Oro, J., in, Chemical Evolution and the Origin of Life, Edited by, R. Buvet and C. Ponnampieruma, North Holland Publishing Co., Amsterdam, 1971, 155 old.
22. Fan, I-Ji, Chien, Yeu-Chin, Chiang, I-Hwa, Scientia Sinica, 19, 805 (1976).
23. James, B.R., Homogeneous Hydrogenation, Wiley and Sons, New York, 1973, 106 old.
24. Bingham, D., Burnett, M.G., J. Chem. Soc. A., 1782 (1971).
25. Bahadur, Nature, 173, 1141 (1945).
26. Bahadur, K., Synthesis of Jeewanu the Proto-cell, Ram Narain Lal Prasad, Allahabad, 1966.
27. Bahadur, K., Ranganayaki, L, Santamaria, Nature, 182, 1668 (1958).
28. Oro, J., Kimball, A., Fritz, R., Master, F., Archiv. of Biochem. and Biophys., 85, 115 (1959).
29. Ventilla, M., Egami, F., Proc. Japan Acad., 52, 21 (1976).
30. Beck, M., Gaspar, V., Ling, J., Unpublished results.
31. Beck, M., Ling, J., Unpublished results.
32. Yamada, S., Wagatsuma, M., Takeuchi, Y., Takeshima, S., Bull. Chem. Pharm., 19, 238 (1971).
33. Brack, S., Louembe, D., Spach, G., Origins of Life, 6, 407 (1964).
34. Hayatsu, R., Science, 146, 1921 (1964).
35. Hodgson, G.W., Baker, B.L., Nature, 216, 29 (1967).
36. Beck, M., Rabai, Gy., Unpublished results.
37. Bowen, H.J.M., Trace Elements in Biochemistry, Academic Press, New York, 1966.
38. Crick, F.H.C., Orge, L.E., Icarus, 19, 341 (1973).
39. Frieden, E., in Protein - Metal Interactions, Edited by, M. Friedmann, Plenum Press, New York, 1974, 1. old.
40. Banin, A., Navrot, J., Science, 189, 550 (1975).
41. Chappell, W.R., Meglen, R.E., Runnels, D.D., Icarus, 21, 513 (1974).

42. Jukes, T.H., Icarus, 21, 516 (1974).
43. Gualtieri, D.M., Icarus, 30, 234 (1977).
44. Farago, M.E., Clark, A.J., Pitt, M.J., Coord. Chem. Rev., 16, 1 (1975).
45. Neilands, J.B., Structure and Bonding, 11, 145 (1972).
46. Hall, D.O., Cammack, R., Rao, K.K., Origins of Life, 5, 363 (1974).
47. Baltscheffsky, H., Origins of Life, 5, 387 (1974).
48. Beck, M., Toth, Z., Unpublished results.